Room Temperature MWIR FPAs: Return of the Lead Salts?

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Abstract

The development of low-cost uncooled thermal LWIR FPAs is resulting in the emergence of a new generation of infrared sensors for applications where affordability is the prerequisite for volume production. Both ferroelectric detector arrays and silicon-based microbolometers are finding numerous applications from gun sights to automotive FLIRs. There would be significant interest in a similar uncooled offering in the MWIR, but to date, thermal detectors have lacked sufficient sensitivity. The existing uncooled MWIR photon detector technology, based on polycrystalline lead salts, has been relegated to single-element detectors and relatively small linear arrays due to the high dark current and the stigma of being a 50-year-old technology.

Introduction

Commercially available lead sulfide (2.8µm cutoff @ room temperature) routinely achieve D*'s of 1 x 10^{11} Jones at 295K. Better lead selenide detectors (4.4µm cutoff @ room temperature) exhibit D*'s in the 1-2 x 10^{10} Jones at 273-295K. Presently, single- element devices or linear arrays of these chemically deposited detectors serve the low-cost military and commercial moderate-performance markets such as guided anti-armor munitions and industrial controls. Commercial companies such as SensArray, currently manufacture multiplexed linear arrays of lead salt detectors. Staring focal plane arrays (FPAs) have not become a reality due to the difficulty in designing a readout integrated circuit (ROIC) that can effectively handle the high dark current associated with 295K operating temperature semiconductor detectors.

In this presentation, we will describe a new detector concept that can reduce ROIC integration well capacity requirements by two to three orders of magnitude and potentially eliminate employment of a chopper or shutter for FPA calibration. The balanced differential input (BDI) detector concept relies on the linearity of photoconductive detectors and effectively nulls out a significant fraction of the dark current before the ROIC input stage.

The polycrystalline nature of the lead salts is easily adaptable to direct growth on any number of substrates, as epitaxy is not required. This potentially lends itself to the development of low-cost stacked multi-color detector technology or even the direct deposition of low-cost detectors onto wafers of ROICs. On a recently awarded DARPA effort, we are exploring a modified molecular beam epitaxial (MBE) technology that will permit bandgap tuning through compositional control. The vacuum deposited material exhibits significantly better uniformity than that from commercial chemical deposition processes.

By the end of 1999, our goal is to demonstrate the first practical staring lead salt focal plane array. This will leverage the extensive investment in advanced cryogenic FPAs and provide a technological face-lift to this familiar and versatile detector technology.

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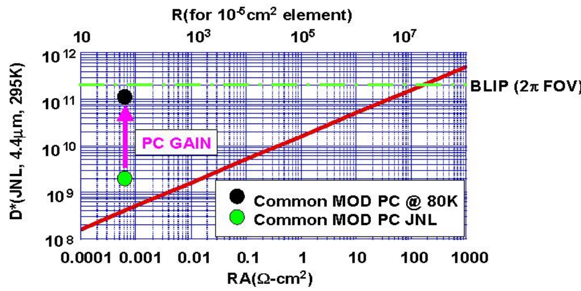
Theoretical Limitations

The theoretical performance limits for a room temperature operation detector is the 180 degree field of view background limited D*. For PbSe with a 4.4μm cutoff and 300K background, this is around 2 X 10^{11} Jones. The following figure is a plot of the Johnson noise limited detectivity for a PbSe detector as a function of resistance-area product. This is compared to the background limit.



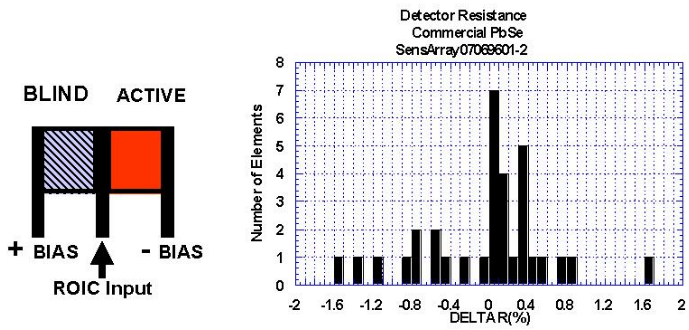
Also plotted is the Johnson noise limited detectivity for a common module mercury cadmium telluride (MCT) detector operating at 80K. Photoconductive gain of more than 100 permits the MCT detector to operate significantly above the Johnson noise limit. A detector's photoconductive gain is a function of the carrier lifetime, the mobility, and the detector geometry. If nominal carrier mobility and lifetime can be achieved in polycrystalline lead salt materials, there is no theoretical barrier to achieving near-background limited detector performance.

Chemically deposited lead salt detectors are often A/C coupled due to excessive low-frequency noise. This is attributed to surface states at the ohmic contact-semiconductor surface or interface states in the oxide barriers between crystallites. It has been our experience that low-frequency noise does not limit sensitivity when care is taken in forming metal-semiconductor contacts and the width of the grain boundaries is minimized.

Balanced Differential Input Detectors

To date, the successful demonstration of staring lead salt based focal plane array technology has been impeded by the inability of existing ROIC technology to integrate the substantial dark currents associated with near-room temperature operation photoconductive detectors. For detector impedance ranging from one to 10 megaohms, a one-volt bias would result in dark current that ranges from 1 to 0.1 microamps. For a well capacity of 100 million carriers, the maximum integration period would range from 160 microseconds to less than 20 microseconds. With the dark noise associated with a midwave photoconductor at 0C, this integration period would not yield useful sensitivity.

We have addressed this ROIC dynamic range issue by developing the balanced differential input (BDI) detector. The BDI detector (shown in the following figure) is comprised of two elements within a single unit cell: a "blind" reference detector and a photoactive detector. These detectors are biased so that the dark currents are essentially equal and opposite in the dark. By combining the current at the input circuit, the integrating capacitor will only need to store the difference between light and dark. Test arrays on chemically deposited PbSe have demonstrated a 100:1 reduction in dark current with common biases on all detectors. This, coupled with the uniformity demonstrated by the vacuum deposited material, could result in a 500x-1000x improvement in the detector's effective impedance. This would increase the minimum integration time for the above example to nearly 20 milliseconds. The longer integration period permits all elements of the FPA to achieve the sensitivity of single lead salt detector.



Balanced differential detector concept employs matched detectors with opposite biases to null dark current. On commercial PbSe detector pairs we can effectively null more than 99% of the dark current.

The dark reference detector need not be equal in size to the photoactive one so long as the reference bias is adjusted to balance the active detector dark current. This can substantially increase the detector fill factor, and hence sensitivity, within the unit cell. Another advantage of the BDI concept is that the reference detector will track the active one over a large operational temperature range because it is made of the same semiconductor as the active detector. This, coupled with the linearity of photoconducting detectors will permit fixed gain and offset correction to provide image uniformity over a range of operating temperatures. Because of the reference detector, it can be shown that the corrected DC offset level will change with temperature, but that the DC uniformity will remain unchanged. This will permit design of a sensor with built-in correction coefficients and eliminate shutters or choppers for field calibration.

For Chopped Integrating Photoconductive Detector:

- Integrate scene and store frame
- Integrate chopper reference and store frame
- Subtract frames for signal

$$Signal_{out} = Signal_{scene} - Signal_{chopper} \cong V_{bias}\,(1/R_{scene} - 1/R_{chopper})$$

For Balanced Differential Input Integrating Photoconductive Detector:

- Integrate scene and store frame

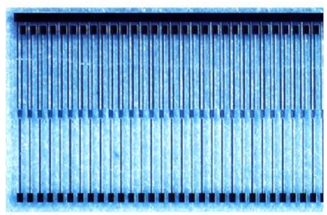
$$Signal_{out} = Signal_{active} - Signal_{blind} \cong (V(+)_{bias}\,1/R_{active} - V(-)_{bias}\,1/R_{blind})$$

for R_{active}(in dark) = $\alpha\, R_{blind}$ and $V(+)_{bias} = V(-)_{bias}$ we get:

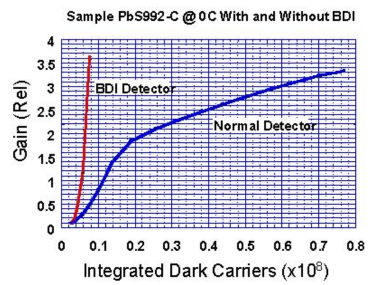
$$Signal_{out} = Signal_{active} - Signal_{blind} \cong V_{bias}(1/R_{active} - \alpha\,/R_{active(DARK)})$$

If α is linear, then BDI is the equivalent to chopping

Multiplexed linear arrays of commercial lead sulfide detectors have demonstrated significant improvement in available FPA dynamic range. The following figure shows the relative detector signal (which is a linear with applied voltage for a photoconductor) as a function of the integrated dark carriers. In BDI mode, the signal with less than 10% of full well filled with dark carriers is higher than a non-BDI detector (with the same optically active area) at ROIC saturation.



32 element BDI test array



Test data on PbS detector in BDI and non-BDI mode. In BDI mode, photo signal is comparable to that in non-BDI mode and ROIC dynamic range is not diminished by integrated dark current.

Summary

We have presented preliminary results for an uncooled photon detector concept that accomplishes dynamic range management in the detector element. By leveraging the community's substantial investment in advanced focal plane technology [for CMOS readout and hybridization] and basing detector development on an existing production methodology, we expect to significantly reduce the time and resources required to bring this technology to market. Such a technology will enable a new generation of moderate-performance, low-cost sensors for both commercial and military applications.

We wish to acknowledge the vision, encouragement and support of Dr. Gene Rubin, which has permitted this effort to become reality.